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Chapter 1

Glued-Laminated Timber

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Structural glued-laminated timber is one of the oldest engineered wood products. It is defined in *ASTM D3737 Standard Method for Establishing Stresses for Structural Glued-Laminated Timber (Glulam)* as "a material glued up from suitably selected and prepared pieces of wood either in a straight or curved form with the grain of all pieces essentially parallel to the longitudinal axis of the member" (1). A stress-rated structural product, glued-laminated timber consists of two or more layers of lumber called laminations, that are nominally 1 or *2* inches thick. The maximum lamination thickness permitted in the United States under *ANSI/AITC A190.1 American National Standard for wood products-Structural Glued-laminated Timber* is 2 inches (2). *ANSI/AITC A190.1* requires that glued-laminated timber be fabricated in an approved (i.e., third-party inspected) manufacturing plant. By joining lumber end to end, edge to edge, and face to face, the size of a glued-laminated timber is limited only by the capabilities of the manufacturing plant and the height and width restrictions imposed by the transportation method.

Species and species combinations commonly used for glued-laminated timber in the United States include Douglas fir-larch, southern pine, hem-fir, and spruce-pine-fir (SPF). Nearly any species or species combination can be used provided its mechanical and physical properties are suitable and their lumber can be glued to meet the requirements of *ANSI/AITC A190.1.* Industry standards currently cover the use of many softwoods (3, 4) and hardwoods (5), and procedures are in place for including other species if and when there is the need (1).

Advantages of Glued-Laminated Timber

Compared with sawn timber as well as other structured materials, glued-laminated timber offers a number of advantages.

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Figure 1. Straight members have been manufactured in lengths of up to 140 ft.

Size

Glued-laminated timber permits the creation of structural members that are much larger than the trees from which the component lumber is sawn. Whereas the forest products industry in the United States once had ready access to large-diameter, old-growth trees that yielded large sawn timbers, the present trend is to harvest smaller trees on much shorter rotations, As a result, nearly all modern sawmills are built to process relatively small logs. However, by combining small pieces of lumber in the form of glued-laminated timber, large structural members can be created. Straight members up to 1100 feet long are not uncommon, with some spanning up to 140 feet (Fig. 1). Members deeper than 7 feet and wider than 20 inches have been produced. Thus, the glued-laminated timber process offers large timbers from small trees.

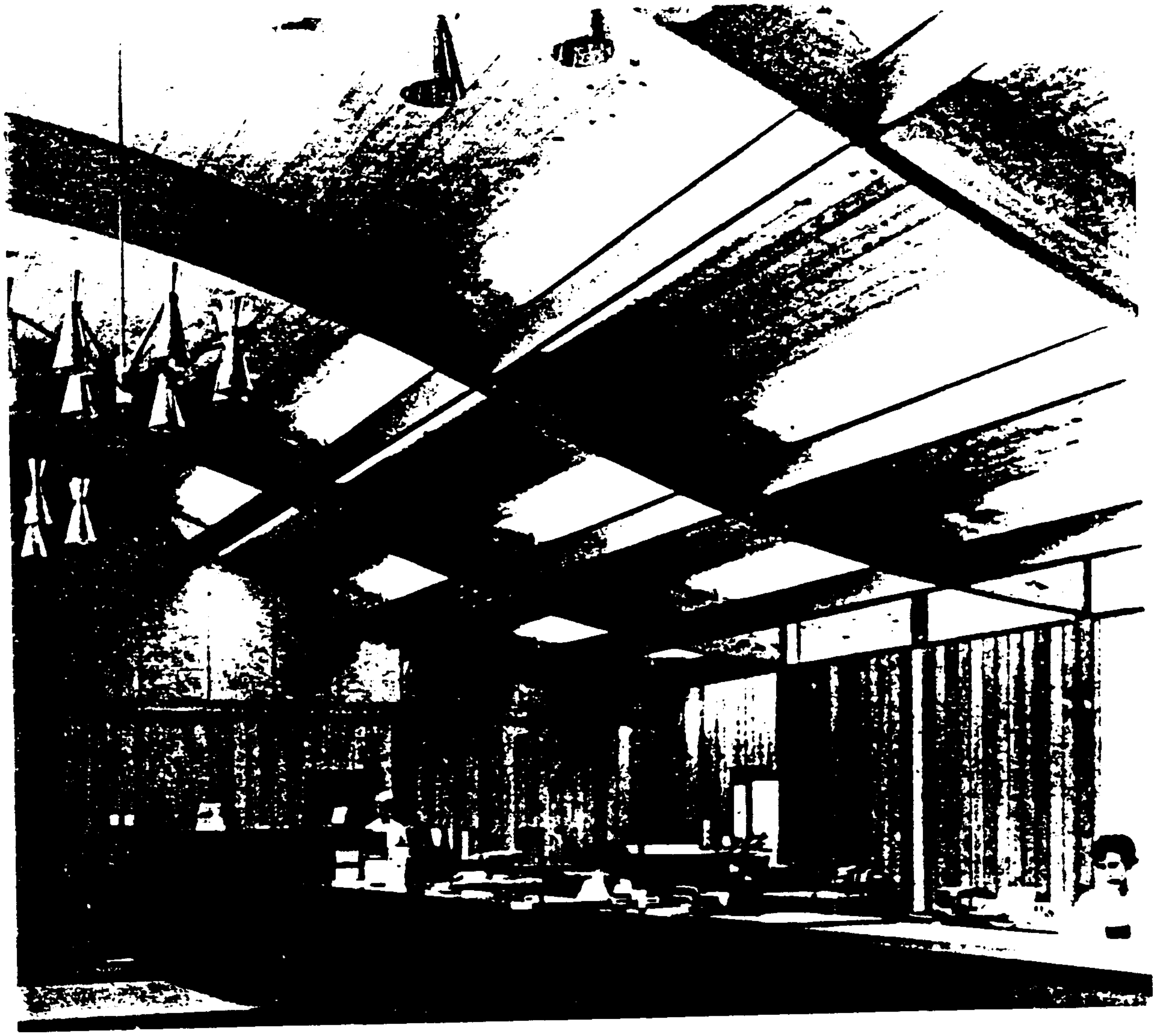

Figure 2. The double curvature of these members is easily obtained by bending laminations during lay-up.

Architectural Freedom

The long, clear spans afforded by glued-laminated timber allow for open floor plans unconstrained by columns. Because of their natural beauty, glued-laminated timbers are most often left exposed as a decorative element In residences, churches, shopping centers. and other public-use structures. By bending the lumber during the manufacturing process, a variety of architectural effects, including arches and compound curves, can be created that are difficult or even impossible

Kiln-Dried Lumber

The lumber used in fabricating glued-laminated timber must be kiln dried prior to assembly; therefore, the effect of checks, splits, warpage, and other defects, which normally develop as sawn timbers dry in service, on the strength and appearance of laminated members is minimized. In addition, structures built with glued-laminated timber can be designed on the basis of seasoned wood, which permits the use of higher allowable design values than can be assigned to unseasoned timber. Thus, there is both an appearance advantage–minimal checking — and a structural advantage — higher allowable design values–when using glued-laminated timber compared with sawn timber.

Variable Cross Section

Structural members may be designed with a variable cross section along their length, as determined by the strength and stiffness requirements of the application. For example, the central section of a glued-laminated timber can be made deeper to account for the increased stress that occurs in this region (Fig. 3). Arches often have a variable cross section for the same reason.

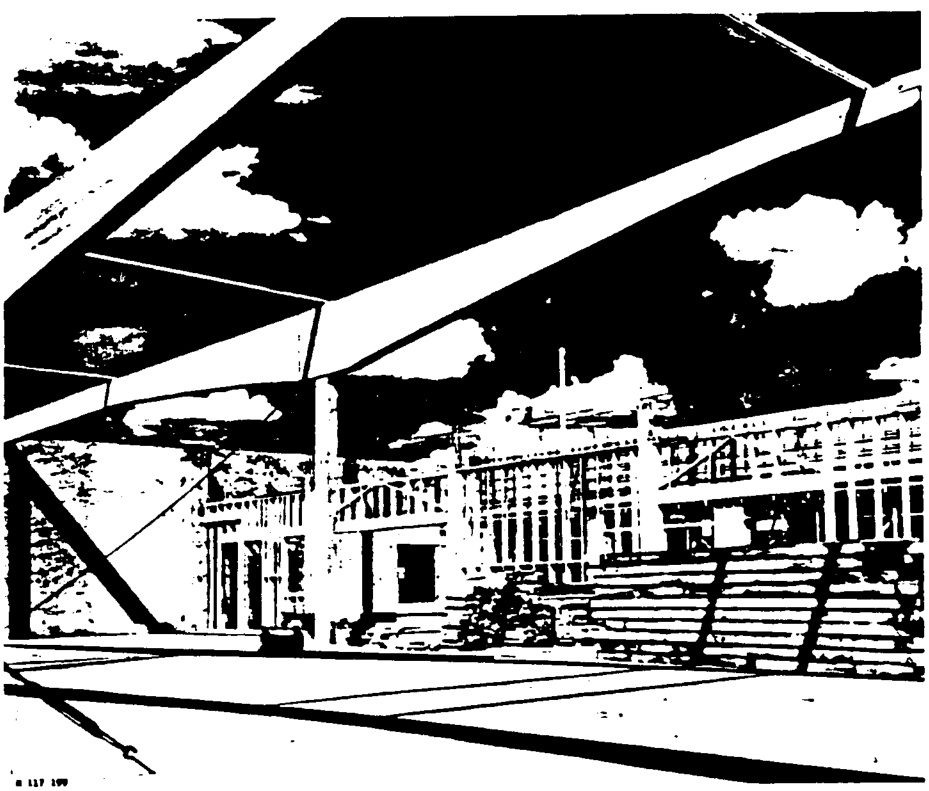

Figure 3. Strength where strength is needed; the central portion of this member has been made deeper to accommodate the increased stress that occurs in this region.

Efficient Use of Lumber Grades

A major advantage of glued-laminated timber IS that the laminating process allows for the strategic placement of different grades of lumber within a member. Typically, the best grades of lumber are placed in the highly stressed laminations near the top and bottom of

the member, while the lower grades of lumber may make up the inner half or more of the member. This means that a large quantity of lower grade lumber can be used for these less highly stressed laminations. Species can also be varied within a member to match the structural requirements of the laminations.

Environmentally Friendly

Much has been discussed and written regarding the relative effects on the environment of using wood, concrete, steel, and other structural materials. Several analyses have shown that wood's renewability, relatively low energy consumption during manufacture, carbon storage capability, and recyclability offers potential long-term environmental advantages compared with other structural materials (6, 7, 8, 9). Although aesthetic and economic considerations are usually the major factors influencing material selection, the environmental advantages of using wood may have an increasingly important effect on material selection.

The advantages of glued-laminated timber are tempered by certain factors not encountered in the production of sawn timber. In those instances where sawn timbers are available in the required size, the extra processing in making glued-laminated timber may increase its *cost to* more than that of the sawn timbers. The manufacture of glued-laminated timber requires specialized equipment, adhesives, plant facilities, and manufacturing skills that are not needed to produce sawn timbers. In addition, because of the large sizes in which both straight and curved glued-laminated timbers are available, shipping, handling, and storage must be considered early in the building design process.

History

Glued-laminated timber, as it is known today, was first used in 1893 to construct an auditorium in Basel, Switzerland. Patented as the "Hetzer System," it used adhesives that by today's standards are not waterproof. As a consequence, its applications were limited to dry-use conditions.

One of the first examples of glued-laminated timber arches designed and built using engineering principles is a building erected in 1934 at the Forest Products Laboratory, in Madison, Wisconsin (Fig. 4). Arches for this building, and for many of the nation’s early buildings framed with glued-laminated timber, were produced by a company in Peshtigo, Wisconsin, which was founded by a German immigrant who transferred the technology to the United States. Several more companies were established in the late 1930s, and using the same technology, fabricated glued-laminated timbers for gymnasiums, churches, halls, factories, and barns.

During World War II, the need for large structural members to construct military buildings, such as warehouses and aircraft hangers, sparked additional interest in glued-laminated

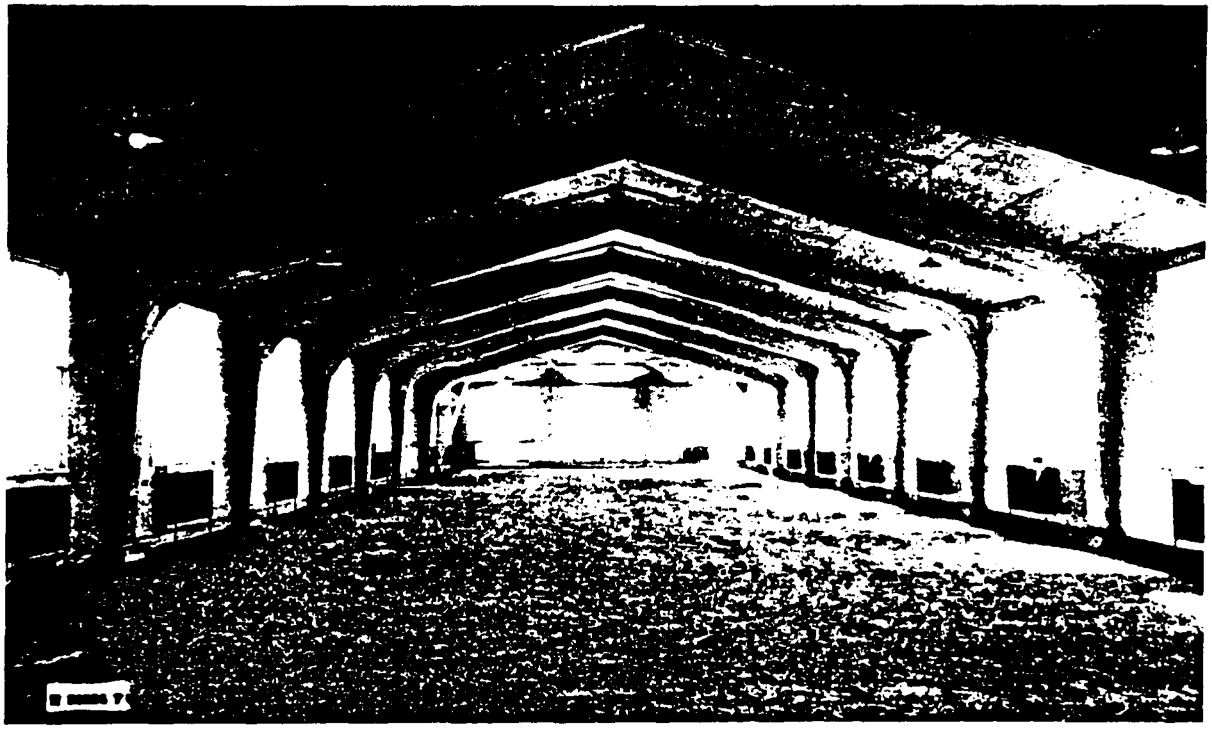

Figure 4. Erected at the Forest Products Laboratory in Madison, Wisconsin, in 1934, this building is one of the first constructed with glued-laminated timber arches designed and built using engineering principles.

timber. The development of waterproof synthetic resin adhesives permitted the use of glued-laminated timber in bridges and other exterior applications where members required preservative treatment. By the early 1950s, there were at least a dozen manufacturers of glued-laminated timber in the United States. In 1952, these manufacturers joined to form the American Institute of Timber Construction (AITC). This association sponsored the first national manufacturing standard in 1963, *CS 253-63 Structural Glued-laminated Timber* (10). AITC has continued to sponsor revisions to the standard. The first was *PS* 56-73 in 1973 that also became an ANSI standard, *A190.1-1973. ANSI A190.1* was revised in 1982 and 1992. The latest version is known as *ANSI/AITC A190.1-1992* (2).

At present, about 30 manufacturers across the United States and Canada are qualified to produce glued-laminated timber according to the requirements of *ANSI/AITC A190.1.* Total annual production is approximately 300 million board feet. Through the 1980s, nearly ail glued-laminated timber production was used domestically. An export market was developed during the 1990s, and a substantial quantity of material is now shipped to Pacific Rim countries, with most going to Japan.

Manufacture of Glued-laminated Timber

The manufacture of glued-laminated timber must follow recognized national standards to justify the specified engineering design values assigned to it. Properly manufactured glued-laminated timber demonstrates a balance in structural performance between the quality of the wood and that of the adhesive bonds.

ANSI/AITC A190.1 has a two-step approach to all phases of the manufacturing process. The first is a qualification step in which all equipment and personnel critical to the production of a quality product are thoroughly examined by a third-party agency. Upon successful qualification, daily quality assurance procedures and criteria are established that are targeted to keep each of the critical phases of the manufacturing process under control. Typically, one employee is assigned responsibility for supervising the daily testing and inspection. The third-party agency makes unannounced visits to the plant to review the manufacturing process, inspect the finished product, and examine the daily records of the in-plant quality assurance testing.

Several third-party agencies provide the qualification services and inspection supervision required by *ANSI/AITC A190.1* including the American Institute of Timber Construction, Englewood, Colorado; American Wood Systems, Tacoma, Washington; PFS/TECO Corporations, Madison, Wisconsin; and Timber Products Inspection, Conyers, Georgia. A current listing of manufacturers who are qualified according to the standard is available from these agencies.

The glued-laminated timber manufacturing process consists of four phases:

1. drying and grading the lumber
2. end jointing the lumber into longer laminations
3. face gluing the laminations
4. finishing and fabrication

A fifth phase–preservative treatment-is necessary in those applications where glued-laminated timber will be used in high moisture content environments or outdoors. A final important step is protection of the glued-laminated timber against moisture absorption and surface marring during transit, storage, and handling.

Lumber Drying and Grading

To minimize dimensional change following manufacture, as well as to take advantage of the higher allowable design values assigned to lumber compared with large sawn timbers, it is critical that the lumber be properly dried. This generally means kiln drying. For most applications, the maximum moisture content of laminations permitted under *ANSI/AITC A190.1* is 16 percent, which results in a member with an average moisture content of about 12 percent. In addition, the maximum range in moisture content permitted among laminations is limited to 5 percentage points to minimize differential changes in their dimensions following face gluing. Some plants *use* lumber at or slightly below 12 percent moisture content for two reasons. One is that the material is more easily end jointed at 12 percent moisture content than at higher values when the adhesive is cured by radio-frequency methods. The second reason is that lumber manufactured at 12 percent moisture content is closer to the average equilibrium moisture content that exists for most interior applications in the United States. Exceptions include some drier areas in the southwest that have lower equilibrium moisture content values and some exterior applications that may have higher values. Matching the moisture content of the glued-laminated timber at the time of manufacture to that which it will attain in service minimizes the shrinkage and swelling, which causes checks and splits.

The average moisture content of the lumber entering the manufacturing process can be determined by sampling from the lumber supply using a hand-held moisture meter. Alternatively, many manufacturers use a continuous in-line meter that checks the moisture content of each piece of lumber as it enters the process. Those pieces with a moisture content greater than a given threshold value are removed and re-dried.

Grading standards published by the regional lumber grading associations describe the natural characteristics and machining imperfections permitted in the various grades of lumber (11, 12). Manufacturing standards for glued-laminated timber like *AITC 117-Manufacturing Standard Specification for Structural Glued-laminated Timber of Softwood Species* describe the combination of lumber grades that must be used to achieve specific design values (4). Two types of lumber grading are used for laminating: visual grading and E-rating.

The rules for visually graded lumber are based entirely on those characteristics that are readily apparent. Lumber grade descriptions list the limiting characteristics for knot size, slope of grain, wane, and other strength-reducing characteristics that naturally occur in lumber. Under the Western Wood Product Association's *Western Lumber Grading Rules* (12), for example, knot size in visually graded western species is limited to:

Laminating grade	Maximum knot size
L1	1/4 of width
L2	1/3 of width
L3	1/2 of width

With E-rated or mechanically graded lumber, the stiffness of each piece is first measured directly with one of several nondestructive methods. Those pieces that qualify for a specific grade are then visually inspected to ensure that they meet the requirement for maximum allowable edge-knot size. The various grades of E-rated lumber are expressed in terms of their modulus of elasticity (E) and limiting edge-knot size. A piece graded 2.OE-1/6, for instance, has a modulus of elasticity of 2.0 million psi and an edge knot no larger than 1/6 of its width.

Manufacturers generally purchase graded lumber and verify the grades through visual inspection and, if E-rated, by testing. To qualify for some of the higher design stresses for glued-laminated timber, manufacturers must conduct additional grading in-plant to identify lumber to be used in the outer tension zone of certain members. High quality lumber with high tensile strength is required for the outer 5 percent of the tension side of a glued-laminated beam. Special grading criteria for "tension laminations" are given in *AITC 117-Manufacturing.* Alternatively, a fabricator can purchase special lumber that is manufactured under a quality assurance system to provide the required tensile strength. Another option employed by at least one manufacturer is to use high tensile strength laminated veneer lumber (LVL) for tension laminations.

Recently, some manufacturers have started using fiber-reinforced plastics on the tension side of glued-laminated timbers to enhance bending strength. Fiber-reinforced members are reportedly up to three times stronger than all-wood members. Because of its exceptional tensile strength, the fiber reinforcement can displace up to 30 percent of the wood required for an all-wood member. The result is a member smaller in cross section and lighter in weight that can span longer distances.

End Jointing

To manufacture glued-laminated timber in lengths beyond those commonly available for sawn lumber, laminations must be made by end jointing lumber. The most common end joint is a structural finger joint about 1.1 inches long (Fig. 5). Other end-joint configurations are also acceptable, provided they meet specific strength and durability requirements. One advantage of finger joints compared with other types of end joints-scarf joints, for example—is that only a short length of the starting lumber is "lost" during manufacture. Finger joints are also easily and quickly made with continuous production equipment. Well-made finger joints are critical to ensure the adequate performance of glued-laminated timber in service. Careful control of the end jointing process at each stage–lumber quality, cutting the joint, application of adhesive, mating lumber, application of end pressure, and curing the adhesive — is necessary to produce consistent, high strength joints.

Prior to manufacture, the ends of the lumber are inspected to ensure that there are no knots or other features present that would impair joint strength. Finger joints are then machined on both ends of the lumber with special cutter heads. A structural adhesive is applied, and the joints in successive pieces of lumber are mated. The adhesive is then cured with the joint under end pressure. Most manufacturers use a continuous radio-frequency curing system that rapidly heats and partially sets the adhesive in a matter of seconds. Finger joints achieve most of their strength at this time; residual heat permits the adhesive to completely cure and reach full strength in a few hours.

Structural finger joints have the potential to attain 75 percent or more of the tensile strength of clear wood for many species of lumber. Because most grades of lumber used in fabricating glued-laminated timber permit knots and other natural characteristics that reduce the strength of the lumber by at least 25 percent below that of clear wood, finger joints are adequate for most applications.

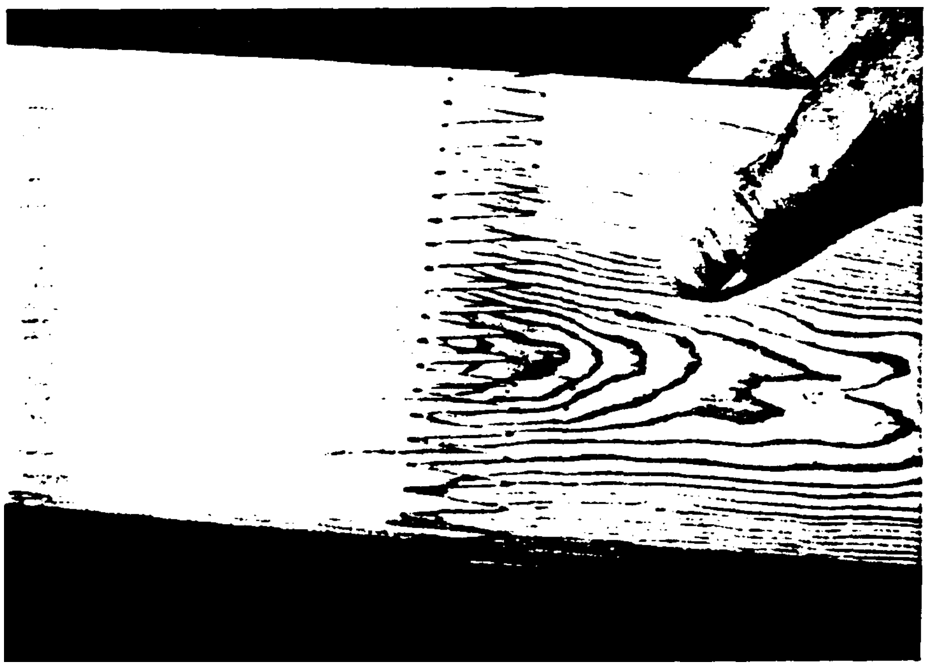

Figure 5. Structural finger joints used in glued-laminated timber typically attain at least 75 percent of the tensile strength of clear wood.

ANSI/AITC A 190.1 **requires that a manufacturer qualify Its production end joint to meet the required strength level of the highest strength grade of glued-laminated timber it is going to produce. This necessitates that the results of tensile tests of end-jointed lumber meet certain strength criteria, and that adhesive durability test results do the same. When these criteria are met, daily quality control testing in tension of full-sized end joints is performed to ensure that the required strength level is being maintained. Adhesive durability tests in which end joints are subjected to repeated cycles of wetting and drying to verify their resistance to delamination are also required.**

A continuing challenge in the glued-laminated timber production process is to detect and eliminate the occasional low strength end joint. Visual inspection and other nondestructive techniques have been shown not to be fully effective in detecting low strength joints. An approach used by many manufacturers to ensure the quality of critical end joints is the use of proof loading. With this method, a specified bending or tension load is applied to critical laminations that will be placed on the tension side of members to verify end joint strength. By applying loads that are related to the strength needed, low strength joints can be

identified. The qualification procedures for proof loading equipment must prove that the loads applied do not damage the laminations that are accepted.

Face Gluing

The assembly of laminations into full depth members is another critical stage in the glued-laminated timber manufacturing process. The proper adhesives and procedures that develop the required interlayer shear strength are determined during the plant's qualification phase. The plant has considerable flexibility in the types of adhesives and procedures that it may use, provided they meet specific shear strength and durability requirements for the species. To obtain clean, parallel, and gluable sunfaces, the best procedure is to plane the two wide faces of the laminations just prior to the gluing process. This ensures that the final assembly will be rectangular and the pressure will be applied evenly. Adhesives that have been pre-qualified are then spread, normally with a glue extruder. Phenol resorcinol is the most commonly used adhesive for face gluing, but other adhesives that have been adequately evaluated and proven to meet performance and durability requirements may also be used.

Laminations are then assembled into the specified lay-up pattern. Straight beams may or may not have a camber built in. Laminations wider than about 11 inches (a 2 by 12) are made by placing narrower pieces side-by-side during face gluing, such that the edge joints in adjacent laminations are offset. Laminations for curved members and arches are glued and cured in curved forms that define their shape. The degree of curvature in a glued-laminated timber is controlled by the thickness of its laminations. In general, the radius of curvature is limited to between 100 and 125 times the thickness of the lamination. As such, only low curvature is possible in members made with nominal 2-inch-thick lumber. Those needing moderate curvature are generally manufactured with nominal 1-inch lumber, whereas laminations 1/2 inch or thinner may be required for members with sharp curves.

After the adhesive is given sufficient time to begin to penetrate into the wood, pressure is applied. The most common method of exerting pressure is with clamping beds in which a mechanical or hydraulic system brings the laminations into intimate contact (Fig. 6). With this batch-type process, the adhesive is allowed to cure at room temperature for 6 to 24 hours before pressure is released. Some of the newer clamping systems combine continuous hydraulic presses and radio-frequency curing to reduce the face gluing process from hours to minutes. Upon completion of the process, the adhesive usually has most of its ultimate strength. Curing continues for the next few days, but at a much slower rate.

The face gluing process is monitored at the lumber planing, adhesive mixing and application, and clamping stages. Adhesive bond quality is evaluated by conducting shear tests on small samples taken from end trim cut off the finished glued-laminated timber. The target shear strength is prescribed in *ANSI/AITC A190.1* and equals about 90 percent of the average shear strength of the wood species from which the member is made. Thus, these adhesive bonds are expected to develop nearly the full strength of the wood soon after manufacture.

Finishing and Fabrication

After the glued-laminated timber is removed from the clamping system, the wide faces (sides) are planed or sanded to remove beads of adhesive that have squeezed out between laminations and smooth any slight irregularities between the edges of laminations. This results in the finished glued-laminated timber being slightly less in width than the dimension lumber from which it was made. The narrow faces (top and bottom) of the member may be lightly planed or sanded, depending on appearance requirements. Edges (corners) are often eased (rounded] as well.

The specified appearance of the member dictates the additional finishing required at this stage of manufacture, but this does not affect the strength or stiffness of the members. Three appearance classes are included in the industry standard: Industrial, Architectural, and Premium (13). Industrial class is used when appearance is not a primary concern, such as factories and warehouses. To some, this is the most natural look for a glued-laminated timber. Architectural class is suitable for most applications where appearance is an important requirement. Premium is the highest appearance class. The primary difference between the classes is the amount of knot holes and occasional planer skips that are permitted. The higher classes require additional attention to filling knot holes and other voids; higher class finishes also increase the cost.

The glued-laminated timber industry is considering the addition of a fourth appearance class called "Framing". Whereas the three previously mentioned classes normally result in a member width less than the lumber width, the proposed "Framing" class would be finished to the same width as the lumber to be compatible with the common widths of framing lumber. This would result in an appearance called "hit and miss" planing and would be intended for uses in which the member is to be covered or the appearance is of minimal importance. In addition, some manufacturers offer members with resawn surfaces that mimic rough-sawn timbers.

The next step in the glued-laminated timber manufacturing process is fabrication. Here final cuts are made, holes drilled, connectors added, and, if specified, a sealer or finish is applied. Depending on the member's intended use, some prefabrication of parts may be done at this point. Trusses may be partially or fully assembled. Moment splices may be fully constructed, then disconnected for transport. Application of end sealers, surface sealers and primer coats, and wrapping glued-laminated timber with a water-resistant covering all help to minimize changes in moisture content between manufacture and installation,

Preservative Treatment

In service environments where the moisture content of a glued-laminated timber will approach or exceed 20 percent, such as in most exterior and some interior uses, the finished member or its lumber laminations should be treated with a preservative as per *AITC 109 Standard for Preservative Treatment of Structural Glued-laminated Timber (14).* Three types of preservatives are used: creosote solutions, oilborne treatments, and waterborne treatments. All these preservative treatments result in a lumber surface that is difficult to bond. Creosote and oilborne preservatives are usually applied to the finished glued-laminated timber after all cutting and boring of holes by the fabricator are completed. The waterborne process can lead to excessive checking if applied to large members and is best applied to the lumber prior to laminating. Recommended retention levels for each preservative type are given in *AITC 109,* along with the appropriate quality assurance procedures.

Creosote treatment is best for glued-laminated timber slated for use in the most severe exposures. It provides excellent protection against decay, insects, and marine borers in uses such as bridges, wharves, and marine structures. Creosote-treated wood has a dark, oily surface that is difficult *to* alter. This, coupled with a distinct odor, restricts its use to nonresidential structures and where there is *no* direct contact with humans. One advantage of creosote is that the water repellency it imparts to treated members renders them much less susceptible *to* the rapid changes in moisture content which can cause checks and splits.

Glued-laminated timber can be treated with oilborne pentachlorophenol dissolved in oil (Type A), light hydrocarbons (Type C), or other solvents listed in P9 *Standards for Solvents and Formulations for Organic Preservative Systems* published by the American Wood-Preserver's Association (AWPA) (15). Type A treatment results in an oily surface; members treated with it cannot be painted. When a paintable surface is needed, Type C treatments should be specified. Penta, as it is called, also imparts water repellency and offers protection against decay and insects, but not marine borers. Glued-laminated timber bridge members in freshwater and utility structures are often penta treated. Other oilborne preservatives used for glued-laminated timbers include copper naphthenate and copper-8-quinolinolate, the only wood preservative approved for use in wood products that may come in contact with food stuffs.

Waterborne treatments can be applied to the lumber prior to the laminating process but are not recommended for use in treating finished glued-laminated timber (16) because of the checks, splits, and warpage that can occur when the members are re-dried after treatment. Preservatives for waterborne treatment conform to AWPA'S P5 *Standards for Waterborne Preservatives* and are based on water-soluble chemicals that become fixed in the wood (17). The protection against decay and insects afforded by these waterborne treatments depends on the depth that the chemicals penetrate into the lumber. Some species are easily penetrated with preservatives — southern pine, for example-and others like Douglas-fir and western hemlock are not. As a consequence, different chemical formulations and treatment processes are used for different species. The challenge in the use of waterborne treatments is to obtain the required strength and durability in the gluelines because the surfaces are more difficult to bond. Manufacturers who are qualified to glue waterborne-treated lumber use special manufacturing procedures.

A major advantage of waterborne treatments is that they result in a surface that is easily finished. From an appearance standpoint, the main effect is that different formulations can produce a green, gray, or brown tint. Care must be used in selecting connection hardware to ensure that it will resist the potentially corrosive interactions with the chemical treatment. Also, glued-laminated timber treated with waterborne preservatives is much more susceptible to changes in moisture content and results in a greater tendency for checking, splitting, and dimensional instability than members protected with either creosote or oilborne treatments.

Fire

Like all wood products, glued-laminated timber is combustible. But because of their large cross-sectional areas and the slow rate at which their surfaces char, glued-laminated timbers exposed to fire will safely carry loads substantially longer than unprotected steel, which begins to soften and lose its strength at about 500°F. When needed, members with a 1-hour fire rating can be made by adding an extra "tension lamination." The fire and flame spread resistance of glued-laminated timber can also be enhanced with the application of fire-resistant surface coatings or pressure impregnation with fire retardants.

Applications for Glued-Laminated Timber

Although the major use of glued-laminated timber is in the roof systems of commercial buildings, it is being used increasingly in residential roof and floor systems and in a multitude of special industrial uses. Wood, in general, has distinct advantages for roof systems because of its favorable strength-to-weight ratio. Glued-laminated timber offers the additional advantage of virtually unlimited flexibility in shape and size.

Commercial and Residential Buildings

Rectangular Beams – Glued-laminated timber beams are popular as the main load-carrying members in flat and low-slope roof systems for single-story warehouses, shopping centers, and factories. The volume of wood required to carry the roof design loads is decreased by using main beams cantilevered over interior supports, with smaller beams spanning between them (Fig. 7). Main members are often spaced 20 to 30 feet apart, with purlins of smaller glued-laminated timber, sawn timbers, wood I-joists, or metal plate connected wood trusses spanning between them. Depending on the snow and other live loads, either 2×4s or 2x6s on edge span from purlin to purlin, which are 8 feet on-center. Structural sheathing is attached directly to the 2-foot on-center 2x4 or 2x6 sub-purlins. Exterior walls are often cast concrete or concrete block. Interior supports may be glued-laminated timber or steel columns. With the main beams erected with a fork lift and the purlin assemblies prefabricated on the ground, large roofs can be constructed in a relatively short time.

Pitched and Curved Beams–Roof systems made with pitched and tapered curved glued-laminated timber beams provide both a pitched roof and an interior space with extra ceiling height, without increasing the height of the supporting wall. Applications for these members include office, retail, institutional, and other buildings that call for long, clear spans and high ceilings.

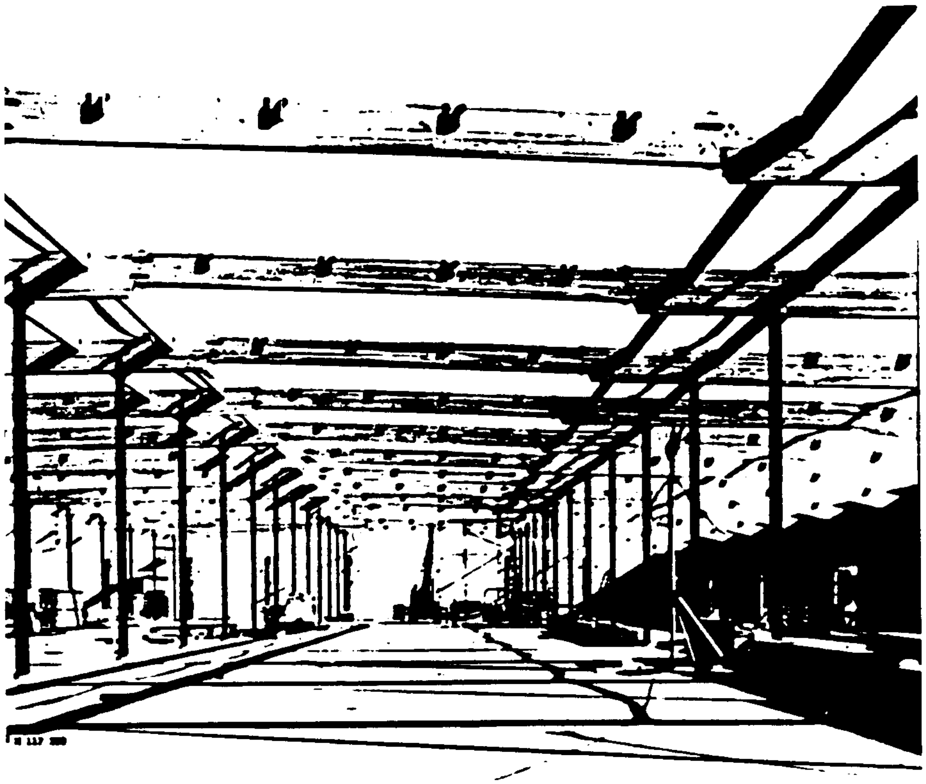

Figure 7. Cantilevered systems are popular in commercial buildings with low-slope and flat roofs.

Trusses–Many kinds of trusses are fabricated with glued-laminated timber. The most common are bowstring, parallel chord, and pitched chord configurations. Glued-laminated timber is particularly suited to bowstring trusses because the top chord can be manufactured to the desired curvature. Connections between chords and webs are most often made with steel plates and through-bolts. Depending on the size and shape of the truss, some pre-assembly of members can often be done off-site.

Headers and Beams for Residential Construction – Many building material suppliers carry stock glued-laminated timbers in standard sizes for use as headers and beams in house construction. Applications include structural ridge beams, exposed roof rafters, floor girders, and headers for large openings, such as picture windows and patio and garage doors. Stock members for residential applications are available In various depths and in 3-1/2 or 5-1/2 inch widths to match walls constructed with 2x4 and 2x6 studs. Other residential uses include stair treads and stringers and fireplace mantels.

Multistory Heavy Timber-Office and retail buildings up to five stories high have been built using glued-laminated timber as the main load-carrying members, most often in the exposed post-and-beam style.

Arches–Glued-laminated timber arches provide for both the efficient transfer of roof loads directly to the foundation and dramatic architectural effects. Their numerous shapes allow architects to create unique structures with sweeping lines. Glued-laminated timber arches have been used widely in bridges, religious structures, concert halls, swimming pool enclosures, skating rinks, and other sports venues (Fig. 8).

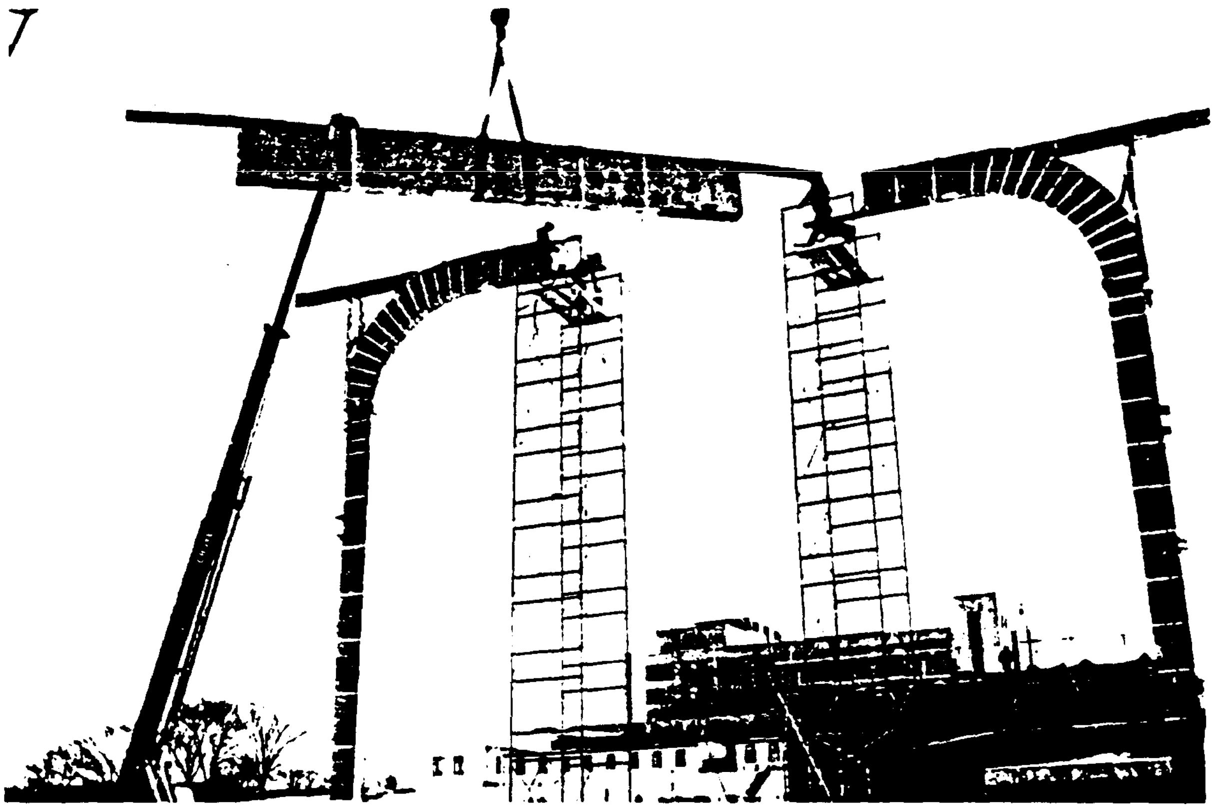

Figure 8. Kraft paper covering these glued-laminated timber arches protects their surfaces during transport and erection.

Domes–The high strength-to-weight ratio of glued-laminated timber makes it advantageous for use in long-span domes for sports arenas, auditoriums, and other assembly-use buildings. These large, support-free circular structures use members arranged in radial rib, VARAX™, or Triax® patterns. Radial rib designs consist of circular arches that radiate outward from the crown (top) of the dome to its base. Both VARAX™ and Triax® domes use glued-laminated timbers arranged in triangular patterns. An example of a VARAX™ structure is the 530-foot-diameter Tacoma Dome in Tacoma, Washington (Fig. 9).

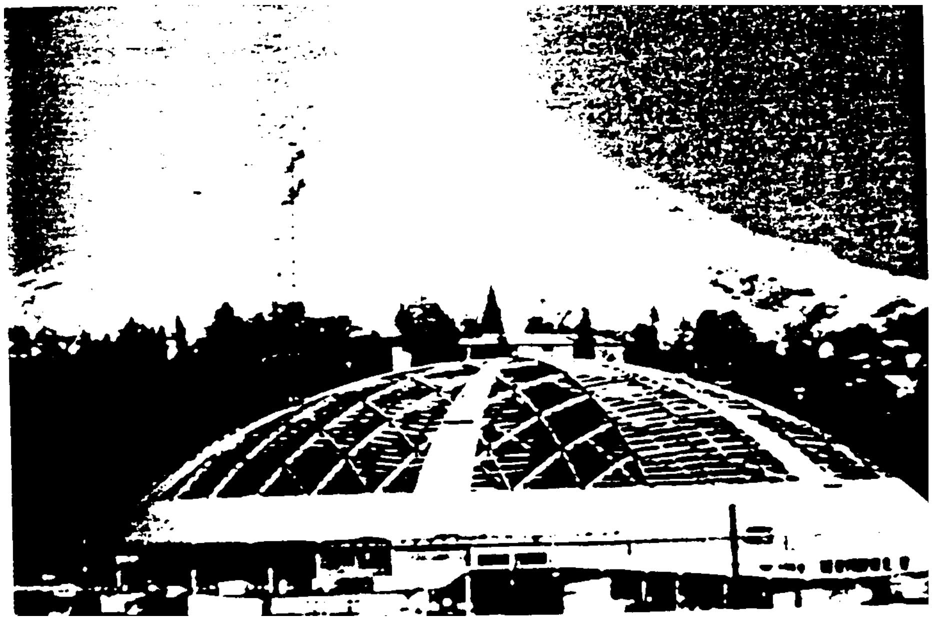

Figure 9. Triangulated members form the roof of the 530-foot clear span Tacoma Dome.

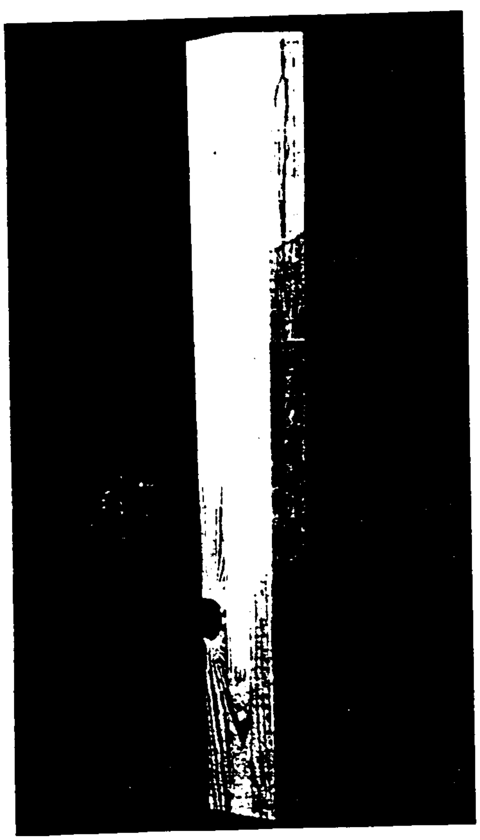

Figure 10. Preservative-treated laminations are used for the end of this glued-laminated post that will be in or near the ground.

Construction Posts–Post-frame buildings are widely used for farm structures and light commercial buildings. Glued-laminated timbers are sometimes used for the posts or wall columns. This provides for the option of making only that part of the post that is embedded in the ground (soil-floor buildings) or near the groundline (slab-on-grade bulldings) with preservative-treated lumber, while using untreated lumber for the remainder (Fig. 10).

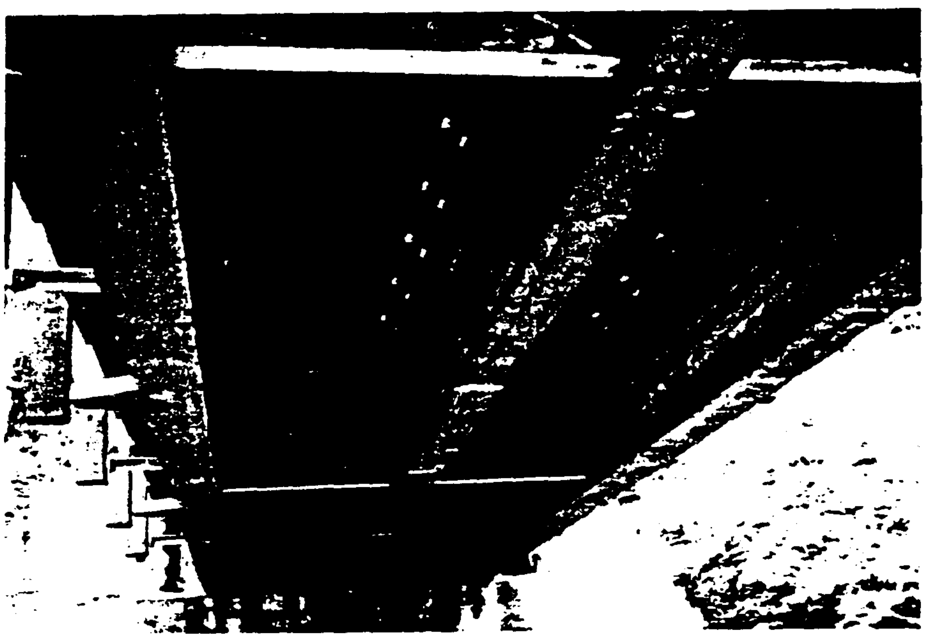

Figure 11. Timber bridge constructed of glued-laminated timber stringers and a transverse glued-laminated timber deck.

Bridges

The main use of glued-laminated timber in bridges is for parts of the superstructure, such as girders and decking (18). One popular type of bridge consists of glued-laminated timber stringers, spanning between supports and glued-laminated timber decking placed transverse to them (Fig. 11). For spans up to 25 to 30 feet, a longitudinal glued-laminated timber deck that requires no stringers is often used (Fig. 12). Special architectural effects can be achieved by supporting the main span with glued-laminated timber arches (Fig. 13).

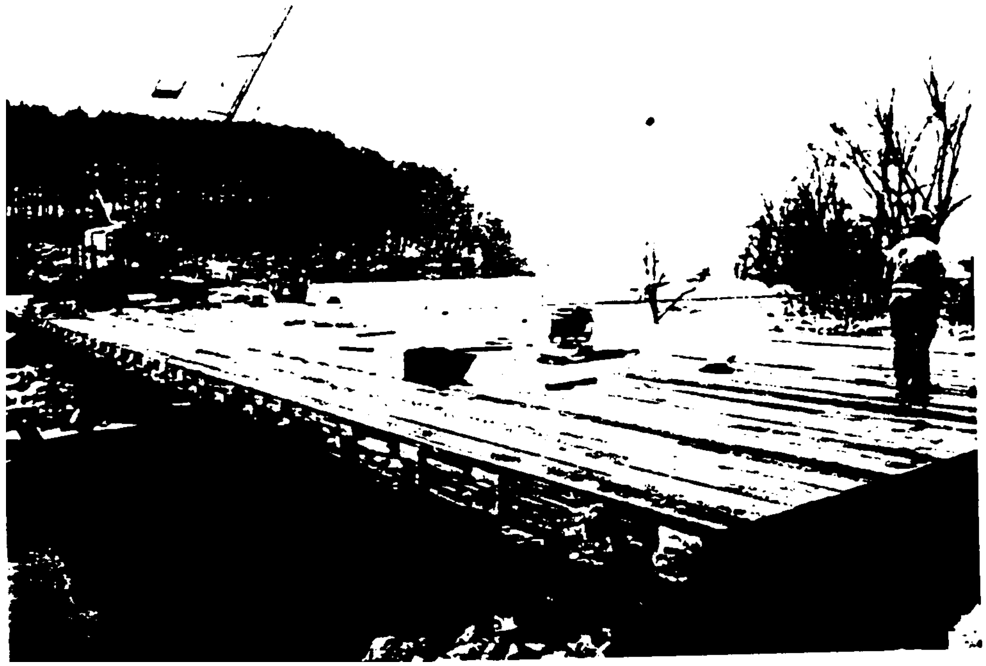

Figure 12. The longitudinal glued-laminated timber deck of this timber bridge does not require stringers.

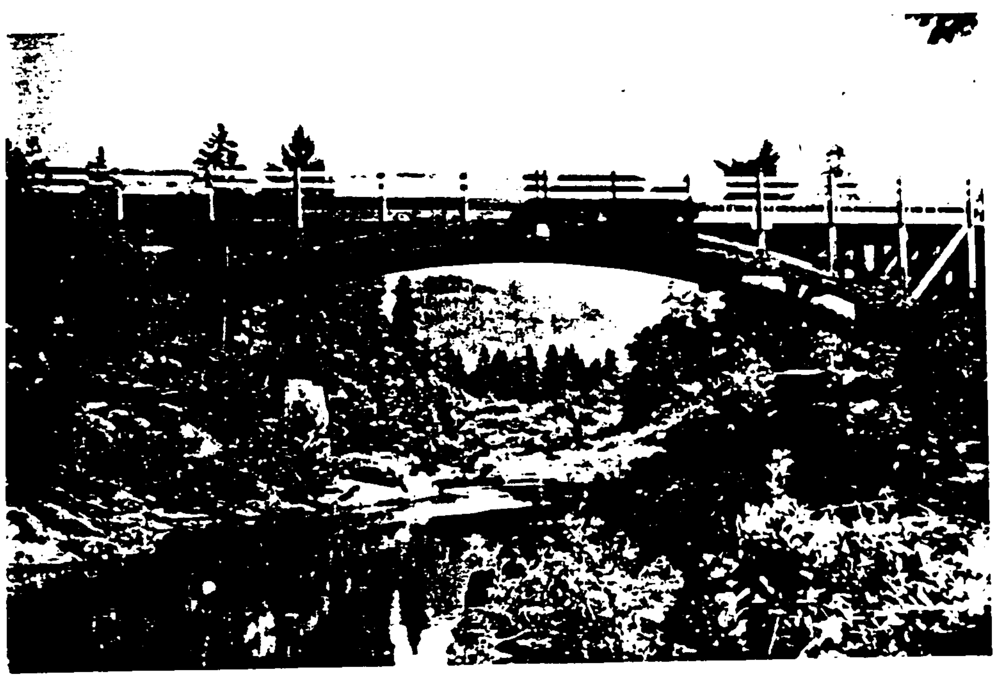

Figure 13. Graceful glue-laminated timber arches support this bridge.

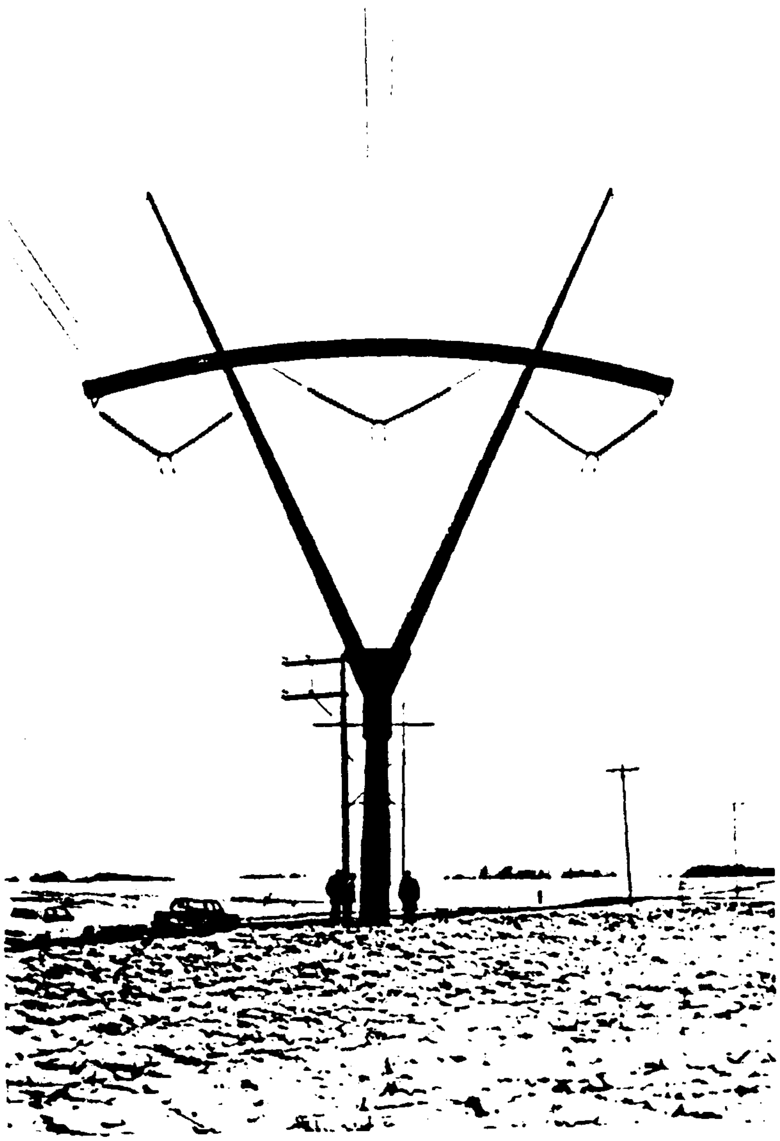

Figure 14. The unique shape requirements of this utility structure were met with glued-laminated timber (courtesy of Hughes Brothers, Seward, Nebraska).

Utility Structures

Glued-laminated timber is used in power transmission towers, light standards, and other utility applications to meet special size and shape requirements that cannot be obtained using conventional wood poles (Fig. 14). Glued-laminated timber cross arms and davit arms are used to support wires on wood poles (Fig. 15).

Architectural sculptures are another example of using glued-laminated timber when special sizes and shapes are required (Fig. 16).

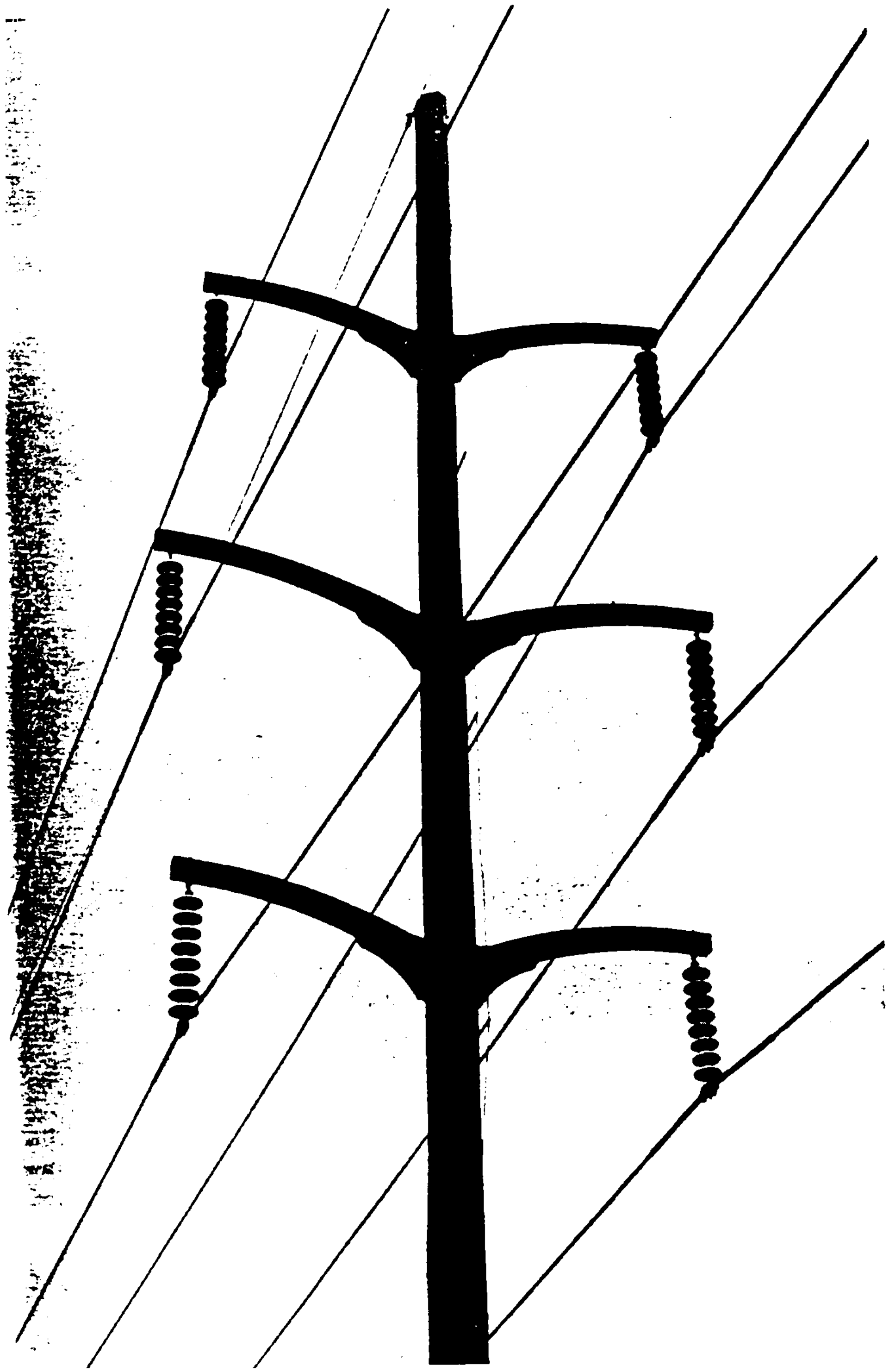

Figure 15. Glued-laminated timber davit arms on a conventional wood pole (courtesy of Hughes Brothers, Seward, Nebraska).

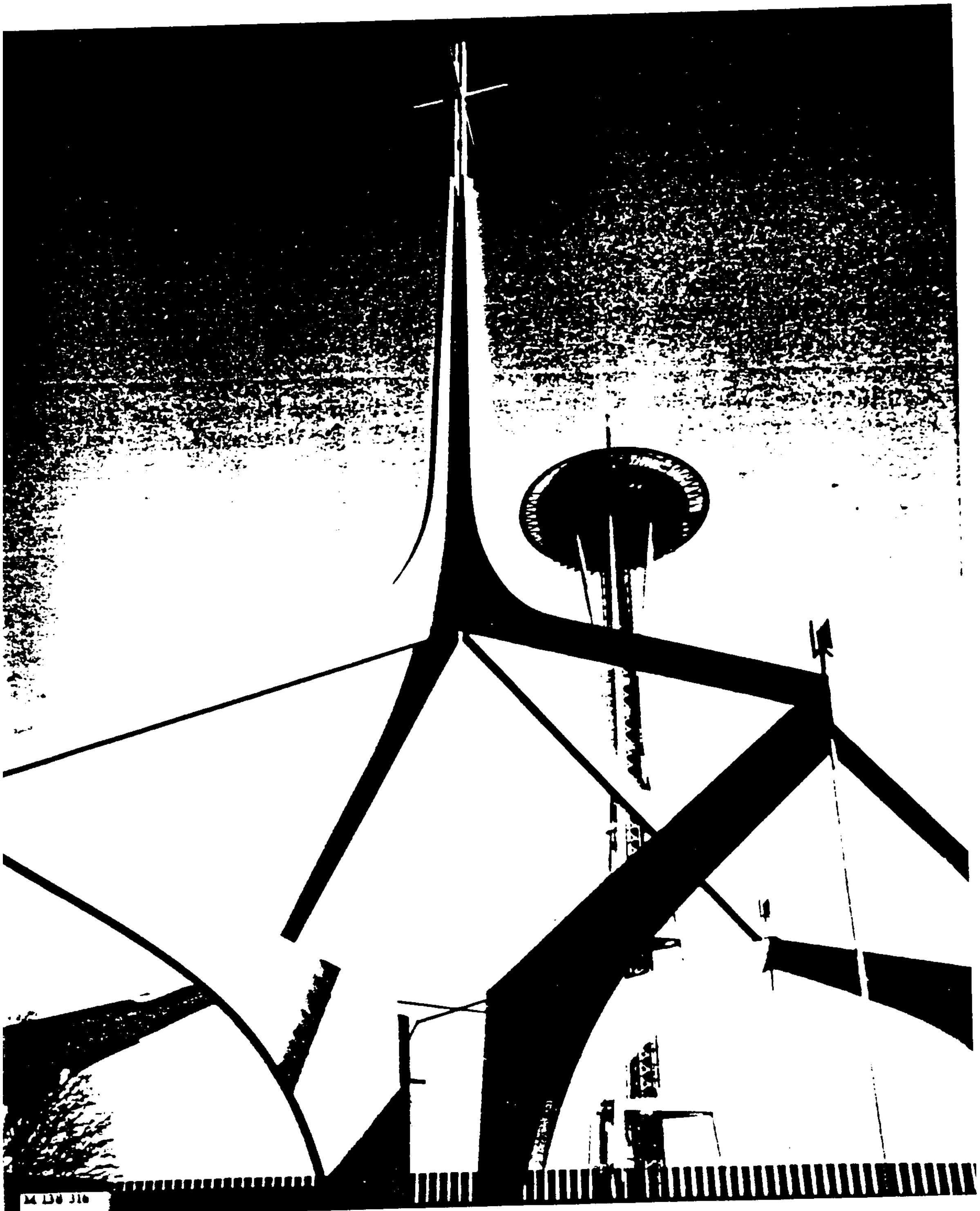

Figure 16. Sculpture illustrates the dramatic architectural effects possible with glued-laminated timber.

Types and Properties of Glued-laminated Timber

Because the laminating process disperses strength-reducing characteristics like knots and slope of grain throughout the volume of a member, glued-laminated timbers have higher allowable design values than sawn timbers. The improved properties are due, in part, to a re-distribution of stresses around low strength regions within the laminations because of the layered construction of glued-laminated timbers. Also, glued-laminated timbers are specially designed to resist stresses based on their intended use as bending, axial, curved, or tapered members by strategically placing higher grade laminations where strength is needed. The configuration or location of various grades of lumber within the cross section of a glued-laminated timber is referred to as a glued-laminated timber combination.

Types

Bending Members-Glued-laminated timbers intended to carry flexural loads are designed using bending combinations. Referred to as horizontally laminated members, these members are based on combinations that provide the most efficient and economical cross section for resisting the bending stress caused by loads applied perpendicular to the wide faces of the laminations. Typically, lower grades of laminating lumber are used for the center portion of the combination, or core, where bending stress is low, and higher grades are placed on the outside faces where bending stress is relatively high (Fig. 17).

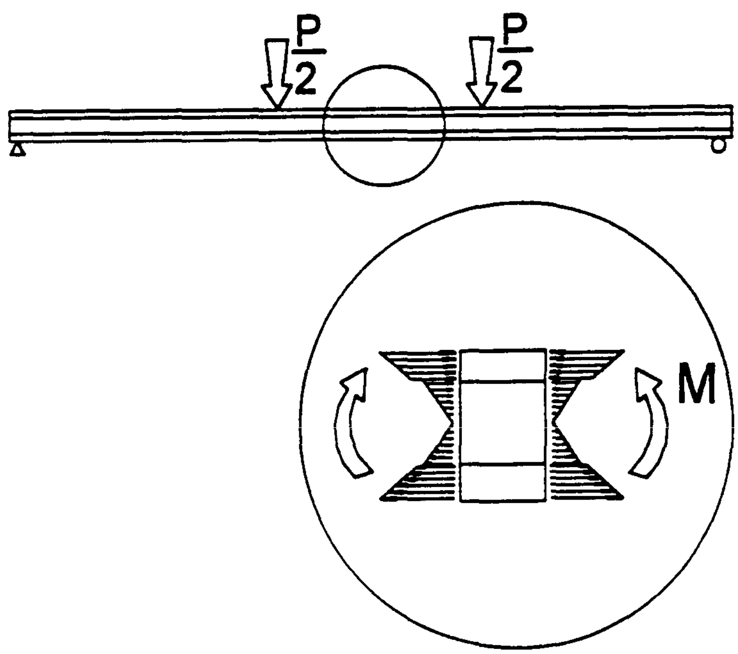

Figure 17. Stresses that develop in a glued-laminated timber bending member when loaded. Discontinuity in stress is due to the difference in the stiffness and strength of the different grades of lumber used for the faces and core.

To optimize the bending stiffness of this type of glued-laminated timber, equal amounts of high quality laminations may be included on both of the outside faces to produce a "balanced" combination. When the goal is to optimize bending strength, the combination can be "unbalanced" with additional high quality laminations placed on the tension side of

the member. The high quality lumber used for the outer 5 percent on the tension side of both balanced and unbalanced bending combination members has stringent requirements for knot size, slope of grain, and the extent of grain deviation.

Unbalanced combinations are suitable for most uses where simple beams are required. When the glued-laminated timber is continuous over supports, however, the combination may need to be designed as a balanced member because both the top and bottom of the beam may be subject to high tensile stresses. In this case, the tension lamination requirements apply equally to both the top and bottom laminations.

Axial Members and Those Loaded Parallel to the Wide Face-Axial combinations were developed to optimize the cross section of glued-laminated timbers designed to resist the axial tension and compression. They are also used for so-called vertically laminated members – glued-laminated timber in which flexural loads are applied parallel to the wide faces of the laminations (Fig. 18). Unlike bending combinations, the same grade of lamination is generally used throughout the cross section of the member. Axial combinations may also be loaded perpendicular to the wide face of the laminations, but use of a uniform lumber grade often results in a less efficient and economical member than with a bending combination. As with bending combinations, different knot and slope-of-grain requirements apply, based on the intended use of the axial combination as a tension or bending member.

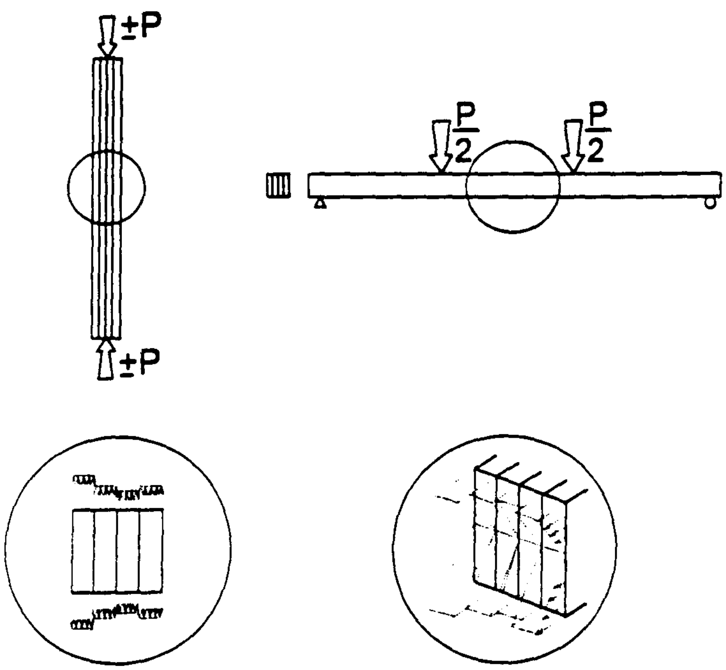

Figure 18. Stresses that develop in glued-laminated timber axial combination members when loaded.

Curved Members–The same combinations that are used for straight, horizontally laminated bending members are also used for curved members. However, an important consideration with these members is the development of radial stresses in the curved portion (Fig. 19) (commonly referred to as radial tension). Loads that tend to flatten or decrease the curvature of a curved member induce radial tension stresses perpendicular to the wide faces of the laminations. As the radius of curvature of the glued-laminated timber decreases, the radial stresses in the curved portion increase. Because of the relatively low strength of lumber in tension perpendicular-to-grain compared with tension parallel-to-grain these radial stresses can become a critical factor in designing curved glued-laminated timber combinations. When loads are applied that tend to increase the radius of curvature (close up the curved member), radial compression occurs. This does not usually control the design.

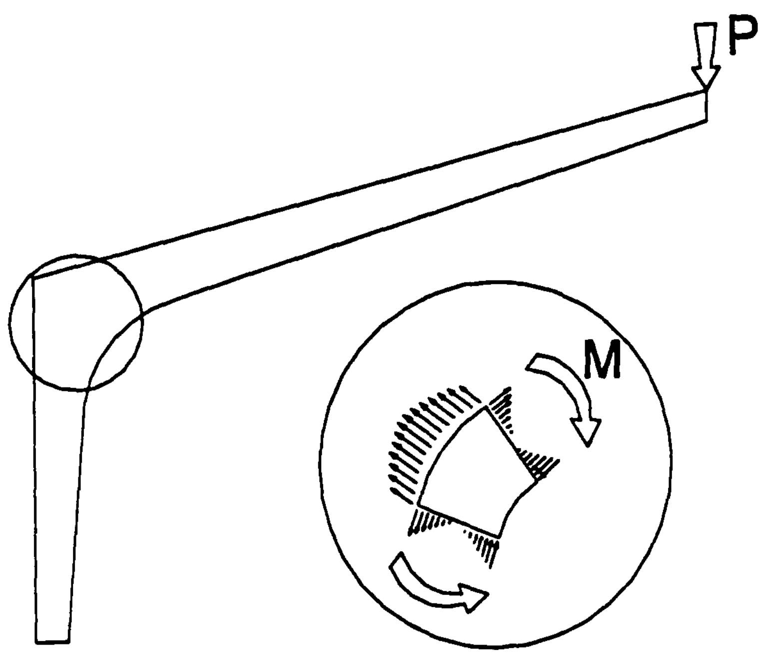

Figure 19. Both bending stresses and radial stresses develop in curved glued-laminated timber while loaded.

Curved members are commonly manufactured with either nominal 1-inch- (actual 0.7 inch-) or 2-inch- (actual 1.5-inch-) thick lumber. It is recommended that the ratio lamination thickness, t, to the radius of curvature, R, not exceed 1/100 for hardwoods are southern pine and 1/125 for other softwoods (1). Thus, the curvature that is obtainable with nominal 1-inch lumber will be sharper than that for 2-inch lumber and sharper from hardwoods and southern pine than for other softwoods.

Tapered Members – Straight or curved beams of glued-laminated timber can be tapered achieve architectural effects, provide pitched roofs, facilitate drainage, and lower wood height requirements at the end supports. The taper is created by sawing across one more laminations at the desired slope. The cut should be made only on the compression

side (top) of a glued-laminated timber, because interrupting the continuity of the tension-side laminations would decrease strength. Common forms of tapered combinations include single tapered (a continuous slope from end to end), double tapered (two slopes that form a peak), tapered both ends (slope at each end of a flat middle], and tapered one end (slope at only one end) (Fig. 20).

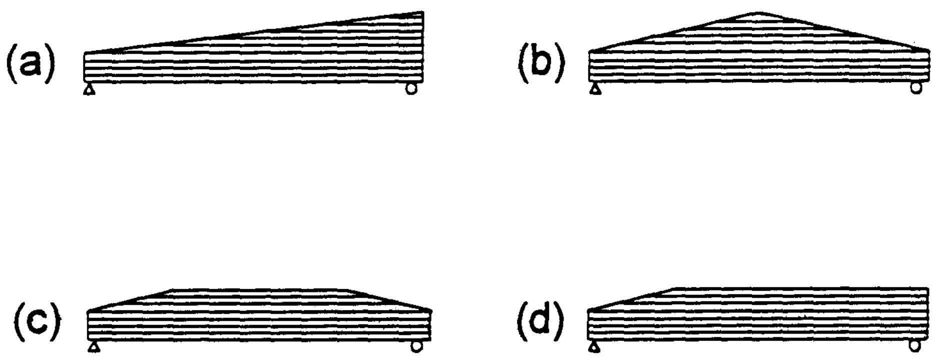

Figure 20. Glued-laminated timbers may be single tapered (a), double tapered {b}, tapered at both ends (c), or tapered at one end(d).

Mechanical Properties

Although a glued-laminated timber is a composite of different pieces of lumber of varying grade, strength, and stiffness that are bonded together, its mechanical properties can be estimated with good results using simplified analysis methods. Industry-accepted methods for establishing and/or estimating the mechanical properties of glued-laminated timber are given in *ASTM D3737* (1).

Modulus of Elasticity–The modulus of elasticity (MOE) of a glued-laminated timber is directly related to the MOE of its' individual laminations. The MOE of a lamination can be determined with a number of different methods, each of which is usually related to the results of a static test in which the lamination is tested at a span-to-depth ratio of 100:1 under center-point loading. Under these conditions, the MOE of the lamination calculated from load-deflection data is essentially unaffected by shear deformation and approaches the true MOE. The MOE of a horizontally laminated member made with a bending combination is taken as 95 percent of the MOE value determined in a transformed section analysis. For a vertically laminated member, the MOE is taken as 95 percent of the average MOE for all the individual laminations. The 5 percent reduction is applied to these types of members to offset the shear deflection that actually occurs in bending members within the normal range of sizes where the length of the member is 15 to 20 times its depth.

The MOE for glued-laminated timbers subject to axial loads is estimated using the weighted average of the MOE values of the individual laminations. Although no reduction for shear deformation is necessary, values published in industry standards applicable to axial loading include a 5-percent reduction. This avoids having two different allowable values of MOE for the same member.

Strength – The strength properties of glued-laminated timber are determined with the use of stress index values and stress modification factors (1). Stress index values are based on the strength properties of clear, straight-grained wood. These values are determined by adjusting fifth-percentile strength values of clear wood by factors that account for safety and moisture content. Properties of clear, straight-grained wood are published in *ASTM D2555 Standard Test Methods for Establishing Clear Wood Strength Values (19).* Because lumber is not clear and straight grained, stress modification factors are applied to the calculated stress indices. The magnitude of the modification factors is based on the strength-reducing characteristics such as knots, slope of grain, checks, splits, and wane that are allowed in the particular grade of lumber being used. The larger or more severe the characteristic, the smaller the stress modification factor.

The primary characteristics involved in determining the stress modification factors for the bending strength of a glued-laminated timber are knots and slope of grain. If the member is horizontally laminated (load applied perpendicular to the wide faces of the laminations), knots present in the outer laminations are more critical than knots in the core laminations. For this reason, the location of knots within a beam, and their effect on strength, is accounted for in an analysis technique called the I_K/I_G method (20). In this method, I_K refers to the moment of inertia of all knots within 6 inches of the critical cross section, and I_G is the gross moment of inertia of the cross section. The ratio I_K/I_G is related to the stress modification factor for bending (SMF_b):

$$SMF_b = \left(1+3\frac{I_K}{I_G}\right)\left(1-\frac{I_K}{I_G}\right)^3\left(1-\frac{1}{2}\left(\frac{I_K}{I_G}\right)\right)$$

For vertically laminated members (load applied parallel to the wide faces of the laminations) subject to bending loads, as well as both tension and compression members, the stress modification factors are also determined based on knot properties of the lumber.

In each case (horizontally laminated bending, vertically laminated bending, compression and tension), the stress modification factors determined for knots are then compared with the stress modification factors for slope of grain. The controlling values–the smaller of SMF with respect to knots or SMF for slope of grain — are used for each of the strength properties.

When estimating horizontal shear values for glued-laminated timber, stress modification factors are assumed to be equal to 1.0, if strength-reducing defects such as checks, splits, and wane are limited in horizontally laminated members. The situation is different for vertically laminated members. If defects exist in any one lamination, then the stress modification factor for each lamination with defects is reduced by half, and the stress modification factor for the entire member is equal to [N - (n/2)]/N. Here N is the total number of laminations in the glued-laminated timber, and n is the total number of laminations with defects.

Stress modification factors are also equal to 1.0 when determining allowable strength values in both compression perpendicular-to-grain and in radial tension. These properties, along with horizontal shear for defect-free laminations, are assumed to be equal to the values for clear wood, because they are not affected by slope of grain or the effects of the laminated construction of the member.

Allowable Design Values

When the stress modification factors, whether governed by knots or slope of grain, are determined for each property, they are multiplied by the calculated stress indices. The products of this multiplication are estimates of the allowable *stress* for glued-laminated timber, not estimates of its actual strength. This is because the clear wood properties on which the stress indices are based were adjusted downward to include a factor of safety and account for duration of load effects. These allowable property values correspond to the tabulated design values for the combinations listed in *AITC 117-Design* (3). In assigning these allowable properties, it is assumed that the end jointing of the lumber and the face gluing of the laminations meet the calculated levels required by *ANSI/AITC A190.1* (2). If tests show that the performance of the end joints does not meet the target level of glued-laminated timber performance, then the allowable properties of the member must be adjusted to reflect the actual end-joint performance.

Physical Properties

With few exceptions, the physical properties of a glued-laminated timber are identical to those of the wood from which it is made. Examples include appearance, working qualities, weathering, decay resistance, chemical resistance, and coefficient of friction. Thermal and electrical properties are point-to-point characteristics that depend on whether the behavior is being analyzed along the length of a lamination or across several laminations. Density and moisture content are volume-based properties that also vary from point-to-point, depending on whether they are being determined for a localized portion of a lamination or an entire cross section.

A critical physical property for glued-laminated timber is the shrinkage and swelling that accompanies changes in moisture content. Residual stresses can be locked into wood adjacent to the gluelines during manufacture when laminations of varying moisture content are bonded together. In addition, because different laminations will shrink and swell by various amounts as their moisture content changes as a result of small variations in density, growth ring orientation, and grain angle, stresses can also develop in service. In severe cases, the residual stresses and in-service movement may be large enough to cause checking near the gluelines. Although almost always an aesthetic problem only, surface checking can be minimized by specifying that the glued-laminated timber be manufactured from lumber at a moisture content close to the equilibrium moisture content of the intended service environment. As previously noted, the maximum moisture content permitted in *AAISI/AITC A190.1* is 16 percent, resulting in an average moisture content near 12 percent, which is appropriate for most covered exterior or interior applications in the United

States. In instances where the equilibrium moisture content is known to be significantly less, a lower moisture content at time of manufacture should be specified.

A rule of thumb that can be used to estimate the extent of dimensional changes is that cross-section dimensions will change 1 percent for each 4 to 5 percentage point change in moisture content. Thus, if the equilibrium moisture content is about 8 percent, a 24-inch-deep member might be expected to shrink about 1/4 inch in depth as it dries from 12 to 7 or 8 percent.

Designing With Glued-Laminated Timber

The design procedures and considerations described here apply only to glued-laminated timber combinations that conform to *AITC 117 Standard Specification for Structural Glued-laminated Timber of Softwood Species* (3, 4), *AITC 119 Standard Specification for Hardwood Glued-laminated Timber (5),* and are manufactured in accordance with *ANSI/AITC A190.1. AITC 117* consists of *Manufacturing* (4), which provides details for the many combinations of glued-laminated timber made from visually graded and E-rated softwood lumber and *Design* (3), which furnishes design values for the strength and stiffness of glued-laminated timber. *AITC 119* supplies similar information for members made from hardwoods. These standards are based on laterally braced, straight members with an average moisture content of 12 percent. For bending members, the design values are based on an assumed reference member size of 12 inches deep, 5.125 inches wide, and 21 feet long. Detailed design information is given in the *Timber Construction Manual* (21).

Tabular Design Values

Allowable design values given in *AITC 117-Design* and *AITC 119* include bending (F_b), tension parallel-to-grain (F_t), shear parallel-to-grain (F_v), compression perpendicular-to-grain (F_{cperp}), compression parallel-to-grain (F_c), modulus of elasticity (E), and radial tension perpendicular-to-grain (F_{rt}).

Because glued-laminated timber may have different properties when loaded perpendicular (horizontally laminated) or parallel (vertically laminated) to the wide faces of its laminations, a common naming pattern is used to specify the design values that correspond to each orientation. Design values for horizontally laminated members are denoted with the subscript "x", and those for vertically laminated members use "y". For example, F_{bx} refers to the allowable design bending stress for a horizontally laminated bending member, and E_y denotes the allowable design modulus of elasticity for a vertically laminated member.

End-Use Adjustment Factors

When glued-laminated timber is exposed to end-use or service conditions other than the reference condition described in the table, the published allowable design values require adjustment.

Volume–The volume factor, C_v, accounts for the known reduction in strength that occurs when the length, width, and depth of glued-laminated timber increase beyond the reference size of 12 inches deep, 5.125 inches wide, and 21 feet long. The decrease is due to the greater probability of the occurrence of critical strength-reducing characteristics, such as knots and slope of grain, in larger volume beams. The volume factor adjustment is given in *AITC Technical Note No. 21, Use of a Volume Effect Factor in the Design of Glued-laminated Timber Beams* (22) as

$$C_V = \left(\frac{12}{d}\right)^{0.10}\left(\frac{5.125}{w}\right)^{0.10}\left(\frac{21}{L}\right)^{0.10}$$

for Douglas-fir and other species, where d is depth (inches); w is width (inches); and L is length (feet). The one exception is southern Pine, where:

$$C_V = \left(\frac{12}{d}\right)^{0.05}\left(\frac{5.125}{w}\right)^{0.05}\left(\frac{21}{L}\right)^{0.05}$$

Moisture Content – A moisture content factor, C_M, is used to account for the reduction in stiffness and strength that occurs when moisture content increases. In *AITC 117-Design,* C_M *is* given as 1.0 when the equilibrium moisture content of glued-laminated timber in service will be 16 percent or less. Under exterior or other conditions that will result in a moisture content greater than 16 percent – a swimming pool enclosure, for example, or when members are in ground contact, the following values apply:

	F_b	F_t	F_v	F_{cperp}	F_c	E
C_M	0.8	0.8	0.875	0.53	0.73	0.833

Loading – An adjustment that accounts for how a member is actually loaded is also necessary, because the volume factor adjustments are derived assuming a uniform load. The loading factor, K_L, recommended in *AITC Technical Note No. 21* and the *National Design Specification for Wood Construction (NDS)* (23) is 1.00 for uniform loading on a simple span, 1.08 for center-point loading on a simple span, and 0.92 for constant stress over the full length of the member. K_L for other loading conditions can be estimated using the proportion of the length of the member subjected to 80 percent or more of the maximum stress, l_o (24):

$$K_L = \left(\frac{0.45}{l_o}\right)^{0.1}$$

Tension Lamination – Special tension lamination provisions must be followed by fabricators in order for the glued-laminated timber beam to achieve the specified design bending strength, Allowable properties tabulated in *AITC 117* and *AITC 119* are applicable to members with these special tension laminations. If the glued-laminated timber combination does not include a special tension lamination, a strength reduction factor must be applied. According to *ASTM D3737,* the appropriate tension lamination factor, C_{TL}, is 1.00 for members with special tension laminations as per *AITC 117* and *AITC 119,* 0.85 for members without tension laminations whose depth is less than or equal to 15 inches and 0.75 for members without tension laminations greater than 15 inches deep.

Curvature-A curvature factor, C_c, is applied to account for the residual stresses in the curved portion of a curved glued-laminated timber created during manufacture. The factor does not apply to the design values for the straight portion of the member, regardless of the curvature elsewhere. The curvature factor is given in the *NDS* as

$$C_C = 1 - 2000\left(\frac{t}{R}\right)^2$$

where t, R, and limits on the ratio t/R are as described previously.

Flat Use–The *NDS* recommends that a flat use factor, C_{fu}, be applied to bending design values when members are loaded parallel to the wide faces of their laminations and are less than 12 inches deep (23):

Member dimension parallel to wide faces of laminations (inches)	C_{fu}
10-3/4 or 10-1/2	1.01
8-3/4 or 8-1/2	1.04
6-3/4	1.07
5-1/8 or 5	1.10
3-1/8 or 3	1.16
2-1/2	1.19

Lateral Stability – Bending and compression members may exhibit lateral buckling if they are not properly restrained at intervals along their length. The lateral stability factor, C_L, accounts for the amount of lateral support applied to a glued-laminated timber and is a function of the member's cross-sectional dimensions and its effective length. Members that are fully supported have no adjustment applied to them (C_L = 1.0). Lateral stability factors

and methods for calculating member effective length for glued-laminated timber are specified in the *NDS* and the *Timber Construction Manual.*

Specifying Glued-Laminated Timber

A specification for glued-laminated timber typically includes wood species; appearance grade; actual dimensions; and finishing and wrapping requirements. For members used in commercial construction, allowable design values are specified, as well as camber, location of connector holes, connection hardware and when appropriate, preservative and fire retardant treatment. Specifying and selecting members for use as beams and headers in house construction is fairly simple. Many retail building materials suppliers carry stock glued-laminated timbers in the sizes (except for length, of course), stiffnesses and strengths needed to carry typical residential loads. Regardless of the application, most manufacturers of glued-laminated timber have engineers in-house who will assist architects, designers and contractors in developing specifications and selecting members for specific applications.

Building With Glued-Laminated Timber

Protection During Transport

To maintain glued-laminated timber at the moisture content of about 12 percent at which it is made, members must be protected from direct wetting from the time they leave the factory until they are under cover in the structure. Types of protection include end sealers, surface sealers, primer coats, and wrappings. The type of protection selected depends on the end use of the member and final finishing requirements. Protection options are detailed in *AITC 111 Recommended Practice for Protection of Structural Glued-Laminated Timber During Transit, Storage, and Erection (25).*

End sealers retard the movement of moisture in and out of members and minimize end checking. If the end-use conditions are such that end checking will be a major consideration, then a sealer should be applied to the fresh-cut ends of members after trimming. In cases where the ends of the members will be exposed in use, a colorless sealer should be used.

Surface sealers on glued-laminated timber increase resistance to soiling, control grain raising, minimize checking, and serve as a moisture retardant. There are two types of surface sealers: translucent penetrating, and primer and nonpenetrating. Translucent penetrating sealers have a low solids content, which results in limited protection. This type of sealer is applied when stains will be used as the final finish. Primer and nonpenetrating sealer coats have higher solids content and provide more protection. Since they obscure The surface of the member, primer and nonpenetrating sealers should not be used when a natural finish or stain is to be applied.

Wrapping glued-laminated timber with a water-resistant covering for shipment provides additional protection from moisture and surface damage. Members can be wrapped individually, wrapped as a solid-piled bundle, or load-wrapped. With the first two techniques, all surfaces of the member or bundle are protected with the wrapping, whereas only the top, sides, and ends of a load-wrapped bundle are covered. Individual wrapping is recommended when appearance is of prime importance and the additional protection is desired throughout all stages of erection. Bundle and load wrapping limits the protection of the members up until the time that they are individually handled.

Unloading and Handling

When unloading and handling glued-laminated timber, care should be taken to prevent damage to surfaces and overstressing of the member. The typically smaller members used in residential construction can often be lifted in place by hand, and the larger members used in commercial projects are hoisted by forklift or crane. To avoid marring surfaces when lifting members by crane, webbed belt slings should be used. Cable slings or chokers should not be used unless blocking is placed between the cable and the sides and corners of the member. To prevent overstressing of members during handling, spreader bars of suitable length should be used when hoisting long members. Whenever possible, members should be lifted on edge.

On-Site Storage

To avoid warpage and prevent overstressing, glued-laminated timber should be stored at the job site on a level area on blocking, spaced to provide uniform and adequate support. If covered storage is not available, the members should be blocked well off the ground at a well-drained location. Stored members should be separated with stickers arranged vertically over the supports so that air circulates around all four sides of each member. If a paved surface is unavailable, the ground under the members should be covered with polyethylene to prevent members from absorbing soil moisture. Lengthy glued-laminated timber should be stored on edge on blocking.

Installation

The typically straight, glued-laminated timber beams and headers used in residential construction rarely require pre-assembly and are simply placed onto their supports one at a time. However, sometimes pre-assembly of complicated glued-laminated timber components is done prior to erection. For examples, trusses are usually shipped partially or completely disassembled; then assembled on the ground at the site and lifted into place. Arches, which are generally shipped in halves, may be assembled on the ground or connected after the two halves have been erected. When components are assembled on the ground, they should be supported on level blocking to permit connections to be fitted properly and tightened securely without damage.

Before erection, the assembly should be checked to ensure that all prescribed dimensions are correct. Erection should be planned and executed in such a way that the close fit and neat appearance of joints and the structure as a whole will not be impaired. Anchor bolts in

foundations, floor slabs, and on top of walls should be checked prior to erection to ensure that they are structurally sound, accessible, and free of obstructions. The weight and balance point of members-especially curved members and arches–should be determined before lifting begins.

Because glued-laminated timbers are typically highly stressed and used in nonrepetitive framing applications, field modifications, such as drilling, notching, and tapering, should not be done without first seeking the advice of the fabricator or a professional engineer.

Construction Details

A common problem associated with glued-laminated timber design is incorrectly accounting for the behavior of the members in a changing environment and exposure to exterior conditions. Recommendations on glued-laminated timber construction details, such as the types, tolerances, and installation of connections, are given in *AITC 104 Typical Construction Details* (26). As mentioned previously, glued-laminated timber can be expected to expand or contract approximately 1 percent for every 4 to 5 percentage point change in moisture content. This degree of dimensional change could cause splitting in the member as a result of the high stresses caused at the connections. Drawings of correctly and incorrectly designed connections are provided *in AITC 104,* which addresses member splitting caused by moisture change. To prevent decay in the wood, connection details are also included that avoid direct contact between the wood and the surrounding material, as well as provide proper drainage in case of moisture entrapment. Although these details are almost always worked out during the building design phase, on-site inspections should be made to ensure that they are being followed during construction.

Bracing

Glued-laminated timbers need to be adequately braced both during construction and after installation. Erection bracing is temporary bracing installed during construction to hold members safely and securely in position until permanent bracing is in place. Permanent bracing is designed such that it becomes an integral part of the completed structure. Bracing may include sway bracing, guy ropes, steel tie rods with turnbuckles, struts, shoes, and similar items. As erection progresses, bracing is securely fastened in place to temporarily carry ail dead loads, erection stresses, and wind, snow, and other weather-related conditions.

Final Alignment and Seasoning

Although the smaller glued-laminated timbers used in residential construction are often fastened with nails and spikes, the large members found in commercial construction are most usually secured with through-bolts inserted into heavy gauge steel straps, plates, and framing anchors. Bolts are only partially tightened during erection; final tightening is not done until the entire structure has been properly aligned. Temporary erection bracing should be removed only after roof and floor diaphragms and permanent bracing are installed, the structure has been properly aligned, and connections and fastenings have been fully tightened. Heat should not be turned on as soon as the structure is enclosed; otherwise, excessive checking may occur as a result of a rapid lowering of the relative humidity within the building. A gradual seasoning period at moderate temperatures should be provided.

Maintenance

The glued-laminated timber in properly designed and built structures should require a minimum of maintenance. Problems that develop are usually related to elevated moisture levels in localized areas of untreated members. For buildings, changing use or building modifications, particularly additions, can introduce sources of moisture. It is imperative that the moisture content of all parts of untreated members be kept below 19 percent. This can be easily accomplished by proper design that does not permit exposure of untreated wood on the exterior, proper operation of mechanical systems that limits condensation, and proper maintenance of the building envelope that does not permit entrance of free water through the roof, walls, or floor systems.

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